Towards Realistic Test Levels for Bulk Current Injection up to 6 GHz

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Abstract— **Due to the increasing clock frequencies and decreasing rise times, the mandatory upper frequency limit for radiated emission and susceptibility testing on electronic modules are increasing up to 3 or even 6 GHz. The Bulk Current Injection test method has widely gained acceptance as alternative immunity test method. Unfortunately, test levels for this test method are only available up to 400 MHz. This paper addresses this issue by proposing a theoretical model based on antenna reciprocity that can be used to predict the worst-case current that is induced into a typical Bulk Current Injection set-up by an incoming plane wave.**

Bulk Current Injection, radiated immunity, antenna reciprocity

I. Introduction

Over the last decades, Bulk Current Injection (BCI) has widely gained acceptance as an alternative or supplementary method for testing the radiated susceptibility of electronic modules. The idea behind BCI is to simulate external, unwanted electromagnetic fields impinging lupon cabling that is most often routed closely to a ground plane, e.g. a chassis. Not surprisingly, it has been standardized by several organizations for a variety of applications ranging from integrated circuits up to subassemblies for automotive or aerospace applications. Its main advantage is that it is a relatively cheap method that is well repeatable and easy to set up.

Although the mandatory upper frequency limits for radiated emission and immunity testing are rapidly increasing up to 3 or even 6 GHz, very little information is available about realistive BCI test levels at such high frequencies. For example, in military and automotive standards limits for BCI are only given up to 200 or 400 Mhz. Only in IEC 62132-3 [1] (BCI for integrated circuits), informative severity limits are given up to 1GHz. But these are taken from the automotive standard for electronic subassemblies [2] and have a constant test level across the entire frequency range. In [3], [4], some indications are already given by means of simulations and measurements that extending the constant limit up to high frequencies might mean that one is overstressing the electronic module under test.

Especially in the early years of BCI, some papers have addressed the equivalence between radiated and injected immunity testing, e.g. [5]. However, these papers also only give results up to 200 or 400 MHz. Moreover, the theoretical model that is used doesn't take into account all high-frequency effects.

In this paper, equivalent worst-case BCI test levels are investigated up to 6 GHz by means of Method-of-Moments (MoM) simulations (NEC-Win Professional [6]) of the BCI set-up combined with a post-processing step based on the reciprocity that exists between a radiating and a receiving antenna.

This paper is organized as follows. Section II summarizes the BCI test levels that are available in standards nowadays. Section III details the theoretical background of the proposed methodology based on antenna reciprocity. Section IV is devoted to the simulation results. Finally, Section V draws concluding remarks.

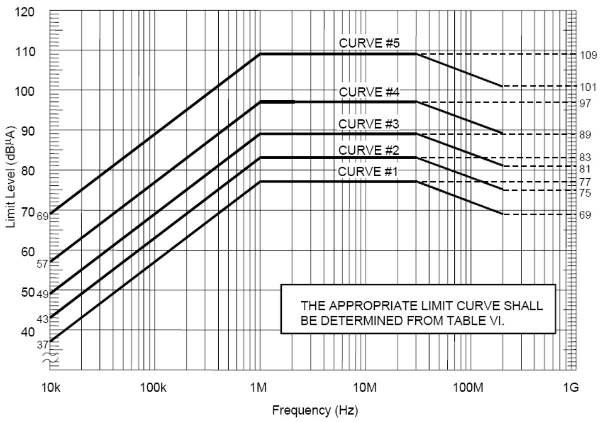

Fig. 1: MIL-STD-461F CS114 calibration limits

II. Existing BCI Test Levels

A. Military Standards

As mentioned above, very little information for BCI limit levels above 400MHz is available. In the military standard MIL-STD-461F [7], the maximum frequency is even only 200MHz (Fig. 1). Different severity levels are defined.

In Table I the correlation between the radiated and conducted limit curves for this military standard is illustrated for the different application classes. It can be seen that for the peak limit (which is between 1 MHz and 30 MHz in this standard) a constant current to field ratio of 1.4 mA/V/m exists which is equal for all limit curves. As can be seen in Fig. 1, the BCI test level decays with a slope of -10 dB/decade above 30MHz.

TABLE I
RADIATED VERSUS CONDUCTED IMMUNITY LEVELS IN MIL-STD-461F FROM 1MHZ TO 30MHZ

Class	RI [V/m]	CI [dBµA]	CI [mA]	Ratio [mA/(V/m)]
1	5	77	7.08	1.42
2	10	83	14.13	1.41
3	20	89	28.18	1.41
4	50	97	70.79	1.42
5	200	109	281.84	1.41

B. *Automotive Standards and Requirements*

Within the automotive industry, the upper frequency in most BCI standards and manufacturer requirements equals 400 MHz. For example, in Fig. 2 BCI test limits are shown as defined by Ford (the EMC test procedures of Ford Motor Company are freely available on the web [8]). The General Motors specification for BCI testing [9] is very similar to the Ford requirements but is not available for free.

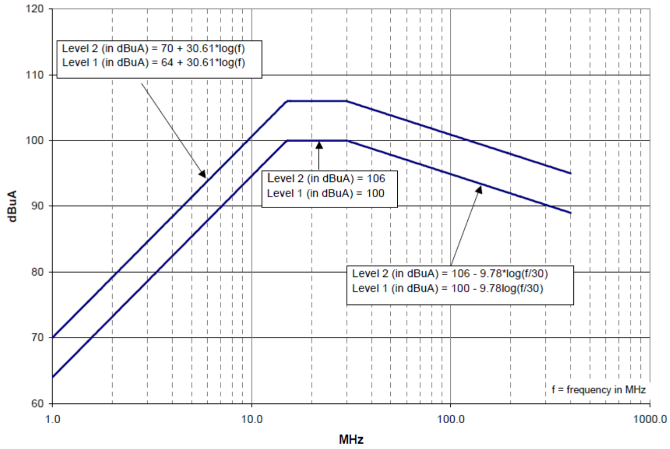

Fig. 2: Ford RI112 BCI requirements

In the Ford requirements, radiated and conducted tests are used as complementary methods instead as alternative methods. BCI test levels are defined up to 400 MHz and radiated immunity test levels are only defined from 400 MHz on. At the 'transition' frequency of the conducted and radiated specification (400 MHz), a ratio of 0.56 mA/V/m is defined.

Although the height of the test harness is similar in all standards and specifications (i.e. 5cm above ground plane), the wire lengths vary as given in Table II.

The main conclusion that can be drawn from both the military and automotive BCI standards is that the BCI test level decreases with a slope of about -10dB/decade at the higher frequencies. This is in contrast with the constant test level that is prescribed in the integrated circuits standard IEC 62132-3.

TABLE II
BCI TEST HARNESS SPECIFICATIONS

Standard	Heigth [mm]	Length [mm]
ISO 11452-4	50 (+10)	1000 ± 100
MIL-STD-461F	50	2000
ES-XW7T-1A278-AC	50	1700 + 300
GMW3097	50	1700 + 300

III. CALCULATION OF THE WORST CASE CURRENT

Consider a typical BCI set-up as illustrated in Fig. 3 comprising a long wire of length l at a height h above a large ground plane. At its ends, the wire connects to the ground plane through the impedances Z_{left} and Z_{right}. Here, we assume that Z_{right} represents the electronic module under test. The purpose is to find the highest possible current that can be induced into Z_{right} by an incoming plane wave $\vec{E}_{inc}$ of 1 V/m for which we don't a priori know from which direction it is falling in.

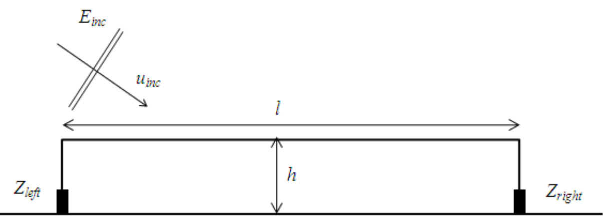

Fig. 3: Typical BCI set-up

To find this 'worst-case' current, the BCI set-up will be first interpreted as a radiating antenna with its source at the location of Z_{right}. The far-field pattern and the input impedance of this antenna are calculated with a MoM simulation. After that the BCI set-up will be interpreted as a receiving antenna onto which a plane wave is impinging.

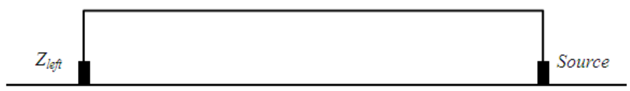

Fig. 4: BCI set-up as a radiating antenna

A. *BCI set-up as a radiating antenna*

In the first step, the BCI set-up is seen as a radiating antenna (Fig. 4). Therefore, the load Z_{right} is replaced by a current source of I_0=1A. The equivalent circuit representation of this radiating antenna is shown in Fig. 5. The antenna impedance Z_{ant} as well as the complete far-field pattern $\vec{E}_{ff}$ can be obtained easily by means of a MoM simulation of the structure. Note that the load Z_{left} is included in the antenna impedance Z_{ant}.

Fig. 5: Equivalent circuit of the BCI set-up as a radiating antenna

B. *BCI set-up as a receiving antenna*

In the second step, the original BCI set-up is seen as a receiving antenna onto which an incoming field $\vec{E}_{\text{inc}}$ is impinging from the direction $\vec{u}_{\text{inc}}$ (Fig. 3). The equivalent circuit representation of this radiating antenna is shown in Fig. 6. Because of the reciprocity that exists for an antenna in radiating and receiving mode [10], the antenna impedance is the same in the equivalent circuits given in Figs. 5 and 6.

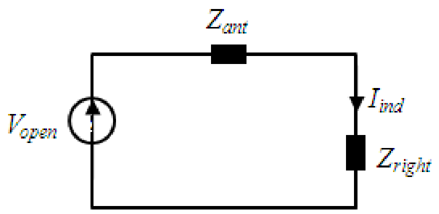

Fig. 6: Equivalent circuit of the BCI set-up as a receiving antenna for calculating the induced current in the load Z_{right}

As is shown in [11], [12], the antenna reciprocity also makes that the open circuit voltage V_{open} in Fig. 6 can be calculated from the information obtained from the BCI set-up as radiating antenna as

$$V_{\text{open}} = -\frac{2j\lambda}{\eta I_0} \vec{E}_{\text{ff}}\,(-\vec{u}_{inc}) \cdot \vec{E}_{\text{inc}}, \qquad (1)$$

with $\lambda = \frac{c}{f}$ the wavelength and $\eta = 120\pi\,\Omega$ the free-space impedance, and I_0=1A. The current I_{ind} that flows through Z_{right} equals

$$I_{\text{ind}} = \frac{V_{\text{open}}}{Z_{\text{ant}} + Z_{\text{right}}}. \qquad (2)$$

C. *Worst-Case Induced Current*

For a fixed BCI set-up (i.e. fixed wire length, wire height, Z_{left}, and Z_{right}) the current induced in Z_{right} will be maximal if the incoming plane wave falls in from the direction that corresponds with the main beam of the BCI set-up's far-field pattern when it is in 'radiating' mode (Fig. 4). Let $\vec{u}_{\text{max}}$ denote the direction of the main beam of the far-field pattern, then the amplitude of the maximal induced current is given by

$$\left|I_{\text{max}}\right| = \frac{2\lambda\left|\vec{E}_{\text{ff}}\,(\vec{u}_{\text{max}})\right|\left|\vec{E}_{\text{inc}}\right|}{\eta\left|Z_{\text{ant}} + Z_{\text{right}}\right|}. \qquad (3)$$

D. *Methodology*

In summary, the proposed methodology to find the worst-case induced current in the BCI set-up is as follows:

i. Replace Z_{right} with a current source of 1A;

ii. Run a MoM simulation to find the antenna impedance and the far-field pattern of the BCI set-up as radiating antenna:

iii. Find the direction of the main beam of the far-field pattern;

iv. Calculate the amplitude of the worst-case current as in equation (3).

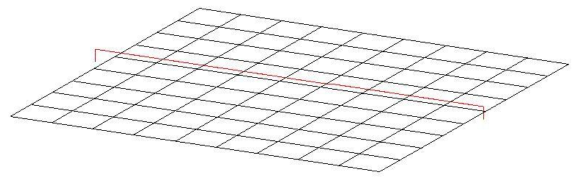

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Fig. 6: Wire model used in the numerical MoM simulations with NEC-Win Professional

IV. Simulation Results

It is straightforward to implement the setup pre-scribed in the military and automotive standards of Section II into a numerical simulation model. In this paper, all simulations were performed using NEC-Win Professional which is based on the MoM technique. Figure 6 depicts the simulation model comprising a long wire of length *l* at a height *h* above a ground plane. The main difference between a 'real' setup and the 'numerical' setup is the infinite ground plane that is used in the simulation model. At its ends, the wire connects to the ground plane through the impedances Z_{left} and Z_{right}. In this paper, Z_{right} is always a 50 Ohm load, while for Z_{left} three different cases were considered: an open, a short, and a 50 Ohm load.

In order to get accurate results, the wire is divided into a sufficient number of segments with respect to the highest frequency being simulated (λ/20 at 6 GHz with λ the free-space wavelength). The methodology described in Section III.D was done for a total of 1000 frequency points that were logarithmically distributed in the between 10 MHz and 6 GHz. At every frequency the far-zone pattern was calculated with a resolution of 1 degree for both the θ and φ angle.

Figures 7 and 8 show the worst-case current induced in the 50 Ohm load Z_{right} for a wire length *l* of 1m and 1.7m, respectively, and this for the three different values of Z_{left}.The height *h* of the wire above the infinite ground plane was always 5 cm. The amplitude of the incoming electric is 1 V/m.

The main conclusion of these simulations is that for the higher frequencies the worst-case induced current indeed decreases with increasing frequency and that the slope is close to the 10 dB/decade that is seen in the limits of the military and automotive standards of Section II.

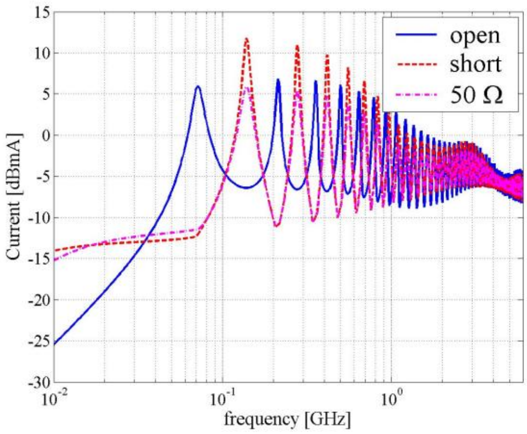

Fig. 7: Worst-case induced current for a wire with length l=1m, height h=0.05m and Z_{right}=50 Ohm. For the load Z_{left} at the opposite end of the wire three cases were considered, namely an open, a short and a 50 Ohm load. The amplitude of the incoming electric field is 1 V/m.

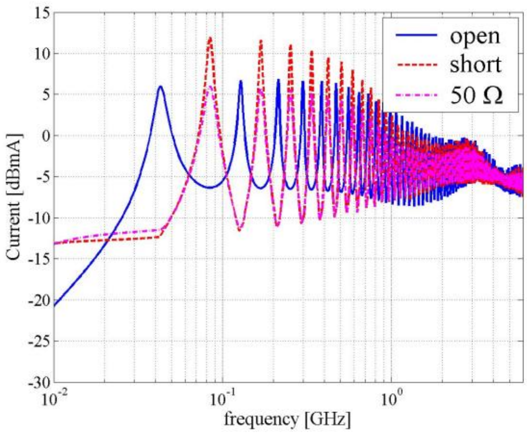

Fig. 8: Worst-case induced current for a wire with length l=1.7m, height h=0.05m and Z_{right}=50 Ohm. For the load Z_{left} at the opposite end of the wire three cases were considered, namely an open, a short and a 50 Ohm load. . The amplitude of the incoming electric field wave is 1 V/m.

Additionally, the simulation results also show that there is a difference in the coupling mechanism between the case for which the wire is left open at the opposite end and the cases for which the opposite end is a short or a 50 Ohm load to the ground plane. The first case resembles a monopole antenna with resonances whenever the total wire length equals $n\lambda/4$ with n an integer value. The latter cases resemble a loop antenna with resonances whenever the total wire length equals $n\lambda/2$ with n an integer value.

Finally, these simulation results seem to indicate that the maximal amplitude of induced current depends on the termination of the BCI set-up at the opposite end of the device under test, but doesn't change much with a varying wire length.

V. CONCLUSIONS

In this paper, a new theoretical model based on antenna reciprocity was proposed to predict the worst-case current that is induced into a typical BCI set-up by an incoming plane wave. The model first calculates the radiation pattern of the BCI set-up in which the device under test is replaced by a current source of 1A. Because of the reciprocity that exists between the a radiating and receiving antenna, one can calculate the induced current in the device under test due to an incoming plane wave. The worst-case current is found by applying this calculation to a plane wave that is falling in from the BCI set-up's main beam.

This methodology was applied to two typical set-ups described in military and automotive standards. The simulation results show that at the higher frequencies the worst-case induced current decreases when the frequency increases. This trend is also seen in the limits of (older) automotive and military standards, but is not present in the (more recent) BCI standard IEC 62132-3 for ICs. This might mean that one is actually overstressing the device under test in the latter standard.

Future work will be orientated towards estimating the high-frequency near-field coupling of typical antennas (Bi-Log, horn,...) to the BCI set-up.

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